An area-based modelling approach for planning heating electrification

Carlos Calderón[a,*], Chris Underwood[b], Jialiang Yi[a], Adrian Mcloughlin[c], Brian Williams[c]

[a]*School of Architecture Planning & Landscape, Newcastle University*
Newcastle upon Tyne, UK, NE1 7RU
[b]*Department of Mechanical & Construction Engineering, Northumbria University*
Newcastle upon Tyne, UK
[c]*Newcastle City Council*
Newcastle upon Tyne, UK

Abstract

Heat decarbonisation is the biggest challenge facing UK energy policy. This paper presents an area-based modelling approach to heat electrification using 17,741 dwellings in the city of Newcastle upon Tyne as a case study. The presented framework has been developed so as to address local energy policy questions on the impact of domestic electrical heating options. These questions reflect significant under-researched challenges such as the quantification of peak electricity demand for heat pumps based electrification options. The presented results show that the electrification of heat at city-scale will have a substantial impact on the local electrical grid infrastructure and provide a first indication of what the potential additional mean and (winter) peak household electricity demand ranges (i.e. 59-95% . This is significantly lower than what might be ascertained from existing literature). Furthermore, the results show that emission savings will be achieved with all electrification options studied but achieving the city's ambitious decarbonisation goals will require more exploration of the urban energy landscape. The paper further underpins the significance of sub-city modelling by enabling policy makers to identify housing neighbourhoods at LV sub-station for area-based delivery. Finally, an integrated modelling approach to cope with forthcoming energy system design challenges at LV scale is suggested.

Keywords: residential buildings, energy, planning, policy, cities, heat electrification, area-based

WORD COUNT: 7900 approximately

*Corresponding author

Email addresses: carlos.calderon@newcastle.ac.uk (Carlos Calderón), chris.p.underwood@gmail.com (Chris Underwood), yijialiang@gmail.com (Jialiang Yi), adrian.mcloughlin@newcastle.gov.uk (Adrian Mcloughlin), brian.williams@newcastle.gov.uk (Brian Williams)

1. Introduction

As a result of the IPCC Fourth assessment reports showing that greenhouse emissions from energy services have contributed to increasing atmospheric GHG concentrations [1, p. 50]; cities being effective agents of change and innovation for climate change issues [2]; and stringent national carbon targets having been set within legal frameworks (e.g. UK Climate Change Act [3]), a current major area of research is to manage urban energy transitions [4] [5]. Notably, modelling efforts for managing urban built environment decarbonisation [1] through local authorities via local actions are seen as a key component for attaining nationally established climate change policy goals [6] [7].

Within urban energy transitions, the decarbonisation of heat is arguably the biggest challenge facing European Union (EU) [8] and UK energy policy over the next few decades [9]. Currently, in the UK, the aggregate heat peak demand (at roughly 300 GW) is approximately 5 times greater than that for electricity [9]. On the supply side, on the other hand, heat mainly comes from burning natural gas (over 70% for domestic, industry and service sectors) [9]. Thus, any innovations to the way heat is delivered to UK buildings could have a significant impact on domestic and industry sectors. Recent findings suggest that centrally (i.e. government) driven processes can be intrusive, whereas "well-designed interventions on an area-based level [10] can be successful and potentially more efficient than targeting individual households" [9, p. 5] . But, how should heat be decarbonised using an area-based approach is an open and complex question and one is difficult to make progress on [11]. It is accepted that there is no one solution for the heating dilemma [11]; there are a range of approaches to heating de-carbonation, from incremental to fundamental changes [11], and there is the need to develop evidence-based heat decarbonisation road maps [12].

As outlined by the Committee on Climate Change (CCC) report [13] , the options for decarbonising heat are: improve energy efficiency; adaptation of natural gas networks (i.e through blending lower carbon gas); electrification of heating through heat pumps; further development of heat networks (e.g. combined heat and power (CHP) plants), and hydrogen networks. This paper, however, focuses on area-based approaches to electrification of heating through heat pumps using the city of Newcastle upon Tyne as a case study. The next paragraphs illustrate the motivation for the study, the local policy challenges faced in domestic heat electrification, and presents the case study area.

2. Case study background

2.1. Motivation

Newcastle City Council (NCC) is a UK local authority committed to energy and carbon emission reduction policies via area-based carbon reduction strategies [14] (i.e. area-based approaches as suggested by [10, p. 48]). In October 2010, Newcastle City Council adopted a citywide Climate Change Strategy and Action plan [15] which was taken further by the 100% Clean Energy vision by 2050 established in March 2016 [16]. Both documents highlight energy use in buildings as significant contributor to carbon emissions. Further, with heating accounting for over 60% of total demand for energy in Newcastle, decarbonising heat,

[1] Decarbonisation should be scientifically understood as defossilisation or getting rid of fossil emissions

domestic heat in particular, is a critical component of achieving the city's decarbonisation goals.

Furthermore, Newcastle is a national path-finder as it is the first local authority in the UK to be piloted in developing a local area energy plan utilising a whole-system analysis approach known as Energy Path Networks (EPN) [17]. Energy Path Networks (EPN) has uniquely combined four aspects of energy system planning in a single tool (see Fig. 1): "a multi-vector (electricity, gas, etc.) approach, allowing trade-off between different energy vectors or networks to be understood; a spatial relationship between buildings and the networks that serve them, so that costs and benefits correctly represent the area being assessed; the ability to compare a large number of combinations of options; optimisation for multiple analysis areas within the study area and for separate time periods" [18]. This means EPN can provide the evidence to a Local Authority to develop local area energy plans which identify a cost effective low carbon urban energy transition (i.e. by 2050 so as to meet the 100% Clean Energy vision in the case of Newcastle) in homes by increasing the use of low carbon energy supply systems in combination with energy efficiency measures and home energy management systems. These local area energy plans are used to facilitate consensus building across the multiple parties involved in local area energy, as well as the transformation of local energy infrastructure, aiding political and commercial decision making and securing private sector investment. This is crucial for local energy infrastructure planning and large area-based roll out of retrofit and new heating schemes, not only for domestic buildings in Newcastle, but for other local authorities across the country.

In the case of Newcastle, EPN analysis has highlighted under multiple scenarios that electrification of heat (e.g. using heat pump based solutions) is often the optimal decarbonisation solution for a significant proportion of Newcastle's housing stock [19] [14] (see Fig. 2.Sankey diagram shows transitioning heat from gas (see Fig. 2a) to electricity (Fig. 2b)). Further, under the most realistically constrained scenario (i.e. as deemed by the EPN stakeholder group [14, p. 88]), EPN analysis suggests that: "electric heat pumps have been selected by the model as the least cost decarbonisation solution in circa 50% of homes" [14, p. 120] and recommends installing individual building electric heat pump based solutions into buildings with suitable characteristics as a development and demonstration project [14]. Consequently, the presented work builds upon EPN's outputs and modelling assumptions in order to support NCC with translating EPN's strategic area recommendations into feasible area-based planning and delivery strategies for heating electrification.

2.2. Local policy challenges in domestic heat electrification

In Newcastle's local energy evidence based plan supported by EPN whole-system analysis, there are areas of the city consistently selected for district heating or individual electric heat solutions whilst other areas show wide variability [14, p. 6]. More specifically, in the most realistically constrained transition scenario there is a large increase in high temperature air source heat pumps and other electric options, including, for instance, small numbers of air source heat pump [14, p. 91].

NCC already has established district heat networks within the city with energy centres at Scotswood, Riverside Dene, Byker and Royal Victoria Infirmary. Newcastle therefore has an advantage in transitioning to district heating (where appropriate) as the technology and its deployment is familiar [14, p. 23]. Further, NCC has been nominated as one of the low

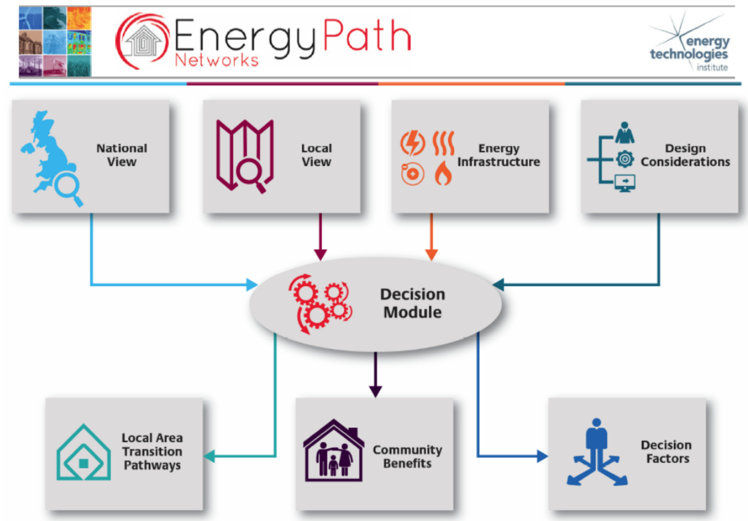
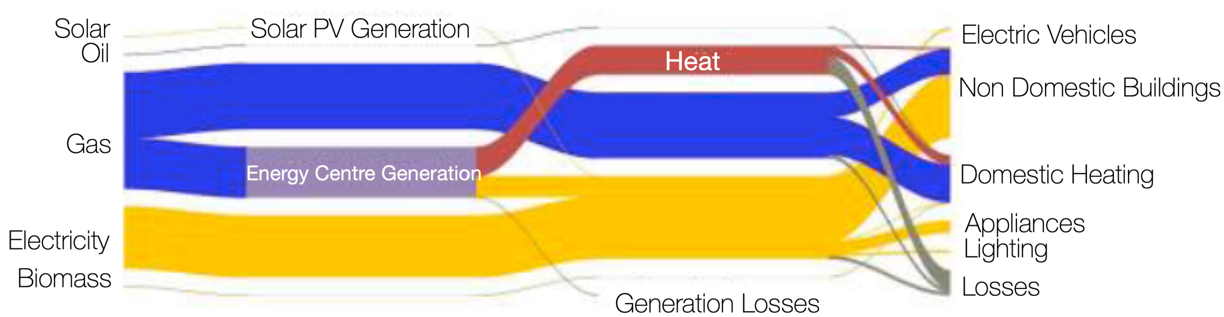
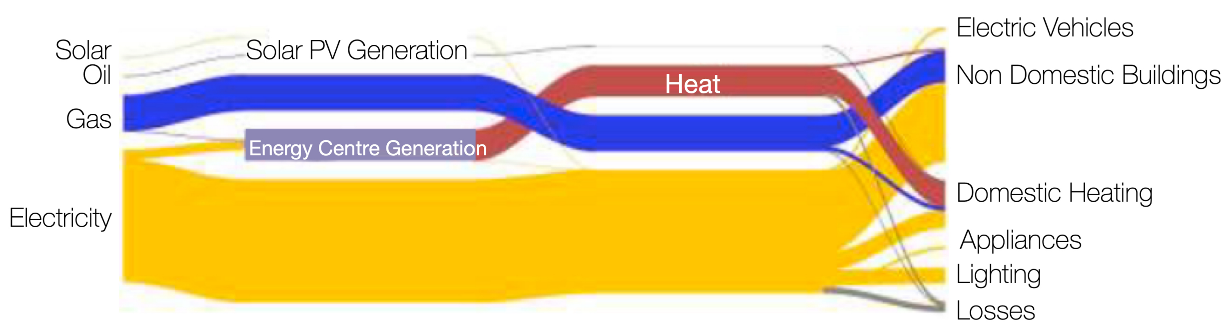


Figure 1: EnergyPath Networks whole-systems modelling framework overview [17]



(a) Business as Usual scenario in 2050



(b) Most realistically constrained scenario in 2050

Figure 2: Sankey diagrams demonstrating how the flow of energy throughout Newcastle, from source to the end user, might change by 2050 as a result of EPN's modelled scenario [14, p. 107].

carbon pioneer UK cities to scope heat network development [20] and funding awarded by the UK government Heat Networks Delivery Unit (HNDU) [21]. As a result, district heating network planning has been developed and outlined for other areas of the city as part of the overall energy master plan [22].

These local energy planning efforts presented local policy makers with the dilemma of selecting (and understanding how to select) between district heating and electric based solutions for decarbonisation of heat in certain areas of the city. Recent studies highlight this known predicament [23], [24] where heat pumps are seen as a potential technology for reduction of fossil fuel generated greenhouse gas emissions and increasing the share of renewables in urban energy production sector [25]. Further, the process of integrating, or not, heat pumps in a district heating system differ for each heating and electricity production and distribution system [25].

Notably, in the Newcastle context, this dilemma was visible for city areas where the predominant heating systems had been identified by EPN as based on low temperature ASHP and GSHP [14, p. 92] and there were also district heating networks planned. Ergo, local policy makers were interested in addressing the following questions:

- What is the impact of heat electrification on the local electricity network for selected areas within the city? In particular, local policy makers were interested in establishing the range of additional electrical demands patterns [26] (i.e. understanding the increase on peak sub-station and annual median electricity demand-Peak) [2].

- How much carbon emission savings will be achieved with the local authority selected heating electrification options (see Section 3.3.3)? Local policy makers were interested in quantifying the potential for carbon emission savings of these options for a selected case study after a heating electrification transition in 2050.

- Is it possible to specific housing neighbourhoods which might be suitable for an area-based heat electrification project delivery? This would enable policy makers to move from the planning to the design phase in heating electrification where energy system design issues such as quantify battery storage design, capacity and behaviour in use, transport, smart control, and renewable energy inputs to the electric grid can be considered.

These local energy planning questions reflect the recent and growing interest in the areas of electrification by design [27] and heat electrification [28] in particular. Further, quantification of local electricity demand increases due to domestic heat electrification have been echoed in the current scientific literature as a significant challenge.

In short, domestic heat electrification can be achieved by a combination of heat pumps and direct electric heating. Local heat electrification will depend on the upstream "carbon intensity of the electricity sector which is expected to fall substantially" [9, p. 8]; it will be driven by spatial requirements (i.e. large gardens for ground source heat pumps); and it will require a prior building energy efficiency upgrades for heat pumps to provide comfortable

[2]Based on the estimated changes in electrical demand patterns, local electrical grid reinforcement costs could be derived but this is outside of the scope of the paper

levels of heating at lower flow temperatures [9]. There are major challenges for the adoption of heat pumps such as high capital costs or lack of supply chain and expertise to design, install, and commission heat pumps [29]. Whilst there are range of policies that could help ameliorate these barriers [29] , Fawcett et al. [29] identifies quantification of peak electricity demand as a current under-researched challenge for adopting heat pumps. In particular, the installation of heat pumps will lead to a significant increase of overall annual median household electricity demand but also, more importantly, to peaks in electricity demand as they operate at specific peak times and for sustained periods such as morning and early periods in winter. Moreover, there is a scarcity of experience and evidence on using heat pumps as a large scale retrofit solution [30]. Quantifying peak electricity demand is a needed step as "widespread electrification of heat would require significant network reinforcement and new generation to meet increased overall demand for electricity and higher peak loads, mitigated through spreading the load over time" [9, p. 8]. This, in turn, will drive the "need for extensive reinforcement of the electricity low voltage network as well as for upgrading substations" [30, p. 36] as domestic dwellings in urban and suburban areas are all connected to underground low voltage (LV) circuits.

2.3. Selection case study area

For this study, the selection of a case study area was based on High Voltage (HV) substation locations as defined by EPN methodology [17]. Case study area 11 (see Fig. 3 and Fig. 4) was one of EPN's original areas of analysis and deemed to be a good case study as it showed variability in terms of the heating systems. Further, Area 11 has 17,741 dwellings (12.92 % of the total number in Newcastle), a good mix of archetypes, transition pathways, tenure/ownership models, demographics, a high level of fuel poverty (i.e. Low Income High Costs [31]), pockets of affluence and deprivation. It also has existing and planned District Heating Network (DHN) schemes in or adjacent to the cluster and existing social capital which could be used for future customer engagement.

In this paper, an area-based bottom-up engineering modelling approach to heat electrification planning is presented. Working with Newcastle City Council in the UK, the above outlined local energy planning questions have been explored in a case study area with 17,741 dwellings in the city of Newcastle upon Tyne. The paper proceeds as follows. The next section discusses the methodology, examining current approaches and reasoning the appropriateness of the selected approach. In Section 3, the validation results are presented whereas in section 4, the building energy modelling and heat pump demand calculations are shown. Finally, the results are discussed whilst outlining a number of recommendations.

3. Methodology

This section first provides the background reasoning on the selected approach in light of local policy questions. Then, data sources, domestic building input data and the modelling framework are discussed.

3.1. Selected approach

There is an extensive variety of models and software tools available in the area of urban energy systems as [32] . Jebaraj and Iniyan [32] review provides a useful model typology as it

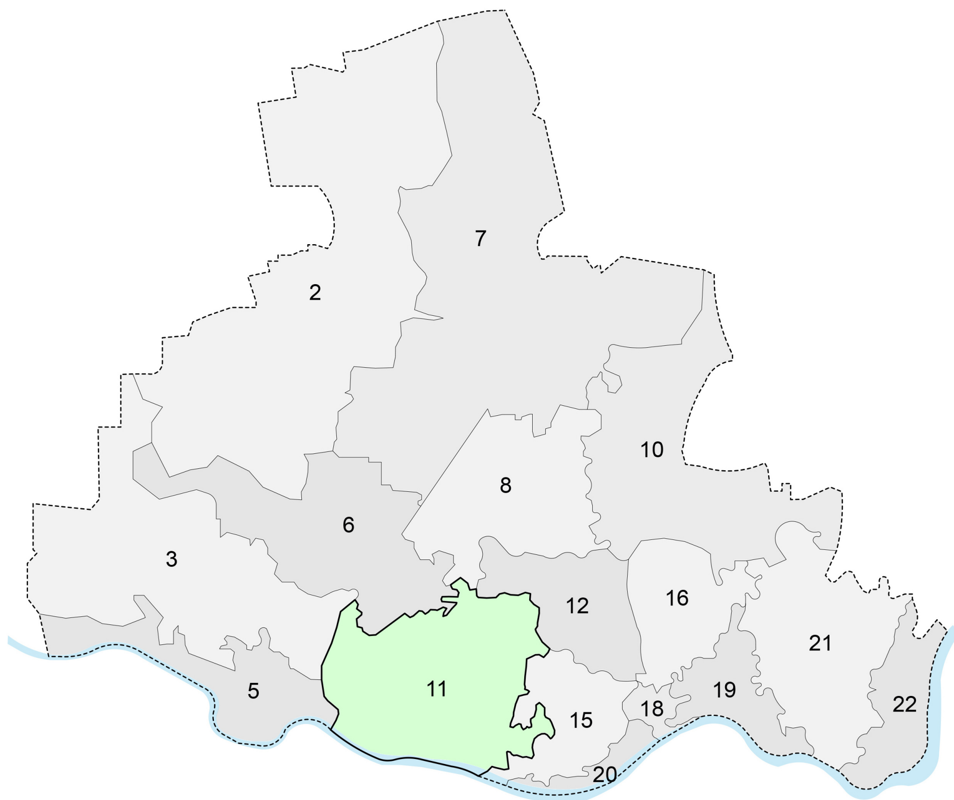


Figure 3: Selected case study area: Area of analysis 11 as per EPN classification. 22 areas of analysis in total within the administrative boundaries of Newcastle upon Tyne.

Figure 4: Selected case study area, Area 11, in relation to geographical reference points: Newcastle City Centre, Gateshead, river Tyne, and Bywell river control station.

classifies models into: energy planning, energy supply–demand, forecasting, renewable energy, emission reduction, and optimization (including neural network and advance AI techniques) models. The study presented in this paper is an exercise in local energy planning (i.e. sub-city level) as a preamble to undertaking more detailed studies for energy systems design in an identified urban area within Newcastle upon Tyne.

Over the past decade there has been a wealth of energy planning modelling initiatives at city and sub-city level as models have become standard tools in energy planning. Generally, it is now accepted that energy planning models can be categorised as "top-down" or "bottom-up" as proposed by [33]. "Top-down" energy models follow a deductive method which starts at a macroscopic level then increasingly subdivide the existing stock into smaller subsections. On the other hand, "bottom-up" models follow an inductive method that calculates the energy consumption of individual or group of houses, then, extrapolate these results to larger areas."Top-down" are less suitable for analyses which focus on a specific area of study within a city [34] whereas "bottom-up" models are not only more suited for this type of analysis but also seen as key planning tools to identify best available technologies and process to achieve given carbon reduction targets [35]. Within "bottom-up" modelling approaches, Swan and Ugursal [33] states that engineering a"bottom-up" modelling approach, unlike statistical one, "has the capability of determining the impact of new technologies (e.g. electrification)" [33, p.1833]. Swan and Ugursal [33] and " is the only method that can fully develop the energy consumption of the sector without any historical energy consumption information" Swan and Ugursal [33, p.1828]. Thus, the presented modelling approach follows up a bottom-up engineering approach as it is based on a simplified analytical model of physical phenomena (i.e. as per [33] definition): BREDEM-12 [36] (British Research Establishment Domestic Energy Model). The presented modelling framework also builds upon previous studies which combined local knowledge and spatially referenced(Unique Property Reference Number - UPRN-) datasets [37] with national datasets (i.e. the English Housing Survey) [38]. These local knowledge and UPRN datasets provide data at the individual building level (of the condition of the housing stock and heating systems) and, in this work, have been applied to a BREDEM-12 so as to establish an energy consumption baseline and the impact of electrical heating options for the domestic stock in localised areas.

The local authority, NCC, was interested in exploring the local policy questions outlined previously (see Section 2.2). To achieve this, the presented approach compares existing and post-transition scenarios using a bottom-up engineering modelling framework. This study follows existing practice within the UK government so as to "explore ways in which heat pumps can be integrated into existing networks, to understand which types of scheme could be economically and environmentally beneficial in a UK context" [39, p. 6]. Specifically, for this type of analysis, a model is used to explore a number of potential heat pumps scheme configurations that are relevant to the area. These configurations are then compared to a so called counterfactual scenario or baseline as shown in [39, 11]. Thus, in this work, there are two scenarios: post-transition (to consistent with EPN methodology [14]) and existing. An existing scenario represents the housing stock as it is today in terms of energy efficiency measures and heating systems. A post-transition scenario represents potential heating electrification options that NCC wants to explore for a housing stock with upgraded energy efficiency measures as a fabric upgrade should always be the precursor to installing any heat pump [9].

Figure 5 provides a methodology overview in terms of domestic buildings (inputs), modelling framework and outputs for validation and scenario (existing and post-transition) testing. Briefly, the methodology consists of a common domestic housing characterisation which has been developed and used with planned housing stock incorporated in the post-transition scenario. Energy efficiency measures and heating systems data and assumptions have been incorporated in the modelling of the existing and post-transition scenarios. The modelling comprises of a bespoke bottom-up community building energy model (CEM) based generally on the BREDEM-12 domestic energy modelling method including heat pump performance metrics taken from a number of recent field monitoring studies. Estimated carbon emission savings are made using current and projected greenhouse gas (GHG) emission factors for the UK. Each methodological component is explained in the following paragraphs.

3.2. Data sources

The presented approach relies on input data for the local domestic buildings and energy networks present within the study area. The primary sources of data for this study have been obtained from previous studies [37], [7] [38], Newcastle City Council [38], and EPN [14] where a full description is available. Table 1 lists primary data sources on building types, conditions and thermal properties. Table 2 notes primary data sources of gas and electricity network data (i.e. network configuration), topography and heat network.

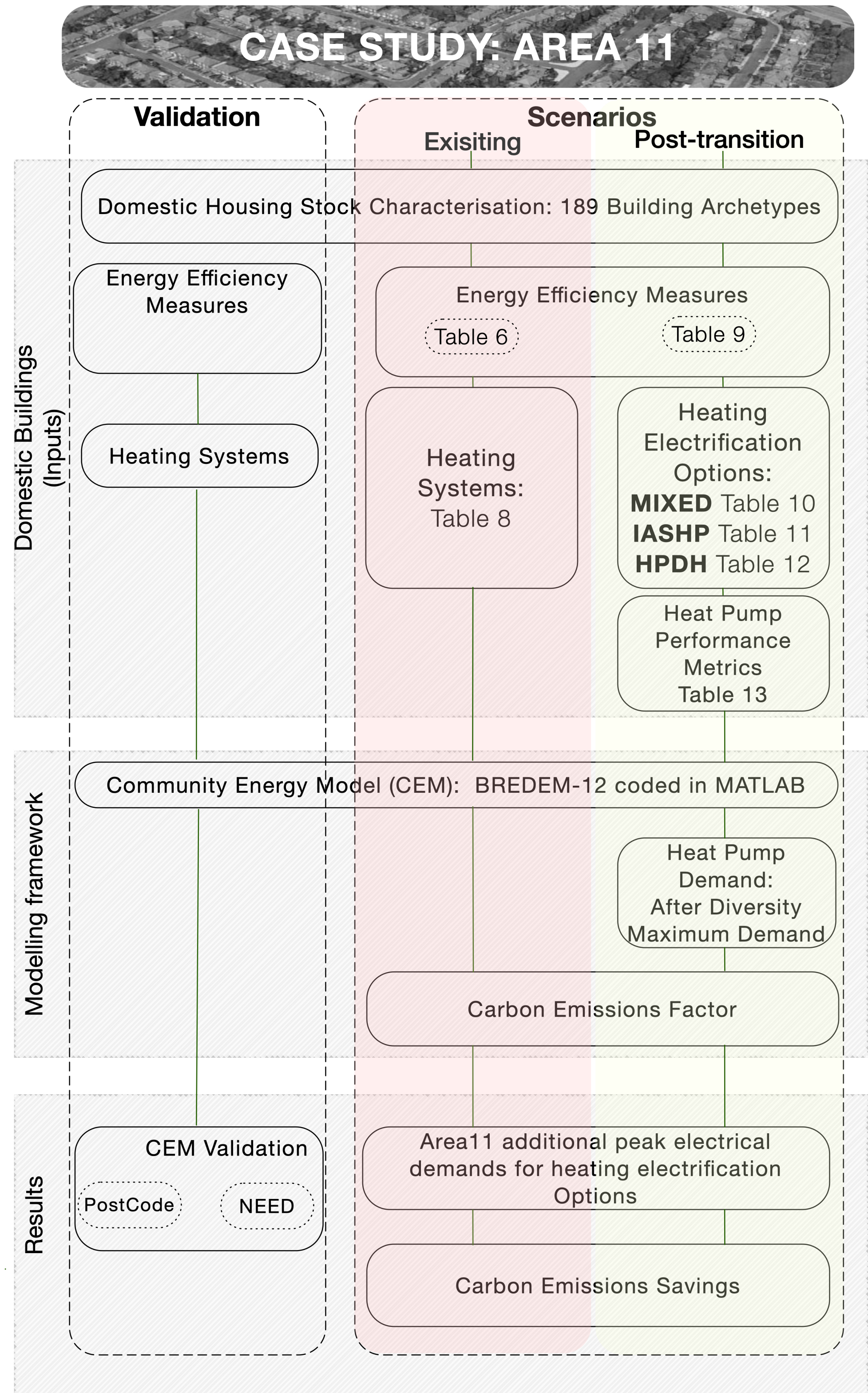


Figure 5: Methodology overview.

Table 1: List of primary data sources used in domestic buildings modelling

Building Data		
Item	Primary Data Sets	Year Published
Domestic building archetype	Geoinformation building classification -OS address base-	2015
Domestic building thermal properties	Newcastle City Council	2015
Domestic building current fabric condition	English Housing Survey - Newcastle City Council	2012
Domestic appliances use profiles	DECC household electricity survey - Building Research Establishment	2012
Domestic building locations and heights	Ordnance Survey	2015

Table 2: List primary data sources used in gas and electricity network modelling

Network Data	
Item	Primary Data Sets
Electricity network: current configuration	Distribution Network Operator (Northern Powergrid)
Gas network: current configuration	Gas Network Operator (Northern Gas Networks)
Existing road network	Ordnance Survey
Heat networks	Newcastle City Council

3.2.1. Model Data Verification

GIS desktop "ground-truthing" of the selected area was carried out to empirically test building classification and matching procedure has correctly identified building classification (e.g. multi-story buildings) and establish modelling parameters such as ratio of window area to gross floor area. Google Street View®was used to spot check whether building classifications corresponded to the "truth" on the ground [3]. The analysis found that detached properties pre-1914 with a total floor area greater than 400 m^2 might have missed classified in the original data. For instance, Fig. 6 shows that dwelling referenced number 543 is in fact 4 terrace houses (see also Fig. 7).

Unit Description			Built up Area			Windows area					Window Area Fraction of GFA	Comments
Reference number	Address	Postcode	Floor area	Num. of Stories	unit total area	Northern Elevation	Eastern Elevation	Southern Elevation	Western Elevation	Total		
543	Benwell Cottage Axwell Park View	NE15 6DP	210	2	420	42	4	28	2	79	0.188	4 Terrace Houses One Detached unit
767	The Vicarage 3 Benwell Lane	NE15 6RS	390	2	780	25	21	28	25	102	0.131	5 Terrace Houses One Detached unit
1751	The Lodge 132 Benwell Lane	NE15 6LX	115	2	230	6	8	11	0	28	0.122	_
4803	Southernwood 1 Fenham Hall Drive	NE4 9DQ	230	2	460	18	32	15	20	88	0.191	_
Archetype Average Window Area | Fraction of GFA											0.158	_

Figure 6: Calculation of ratio of window area to gloss floor area for detached houses pre-1914 with a total floor area greater than 400 m^2

3.3. Domestic Buildings

The domestic housing stock characterisation, input data used for the existing and post-transition scenarios, and other considerations taken account are described below.

3.3.1. Domestic housing stock characterisation

Area 11 housing stock has been characterised using building archetypes. Building archetypes are based on type, size, and age as dwelling's size and type are the most significant predictors of energy consumption [40]. In particular, our model has 36 building archetypes based on type (nine house types) and age (four age bands) grouped by building regulations which are

[3]Four properties were checked for all house types and corresponding periods used in BREDEM-12 CEM

Figure 7: Example of missed classification: Google Street View of 4 terrace houses which are miss-classified as one large pre-194 detached house.®

mapped onto the spatially referenced (UPRN) Geoinfo building classification. Furthermore, our model has 7 floor area bands as provided by Newcastle City Council [37] [14] what means that CEM has a total of 189 feasible building archetypes (see Table 3). As a result, it is feasible to break down the housing stock by, for instance, house type (see Table 4) or age (see Table 5) for the area of analysis.

Table 3: House types, floor and age bad in CEM

Age band	House types	Floor band
	Detached	
Old -pre-1920	Semi-detached	$42.5\,m^2$
	End terrace	$61.3\,m^2$
	Mid terrace	$80.1\,m^2$
Intermediate (1920-1979)	Purpose-built flat, mid floor	$91.3\,m^2$
	Purpose-built flat, top floor	$133\,m^2$
Recent (1980-present)	Converted flat, top floor, mid terrace	$250\,m^2$
	Converted flat, mid floor, mid terrace	$400\,m^2$
New (plan new build)	Converted flat, mid floor, end terrace	

Table 4: Breakdown of housing stock by house type in area of analysis.

House type	Number
Detached	1,297
Semi-detached	4,286
Mid terrace	4,839
End terrace	2,193
Purpose-built flat	4,878
Converted flat	248

The existing housing stock has been characterised as per Table 3 and includes all houses types and ages (see tables 4, and 5) with the exception of those planned as new built (2,952. See Table 5).

Table 5: Breakdown of housing stock by house age in area of analysis.

Age band	Number
Old (pre-1920)	3602
Intermediate (1920-1979)	10302
Recent (1980-present)	885
New (plan new built)	2952

3.3.2. Existing: Energy efficiency measures and heating systems

In terms of energy efficiency measures for the existing houses, a proportion of them had already had fabric insulation upgrades. Data for the houses with improvements was given by Newcastle City Council. Furthermore, the standard of thermal insulation was matched to the age band of each house based on a general perspective that cavity wall construction (amenable to insulation upgrading) did not become common in UK house construction until the 1920s. A further consideration here is that the first edition of the UK Building Regulations to introduce mandatory fabric insulation measures became statutory in 1984. The number of existing houses with double glazed windows was derived from city council surveys [37] all other houses are assumed single glazed with wood frames. Existing loft insulation measures were derived from the city council data [38] [14];. Table 6 and 7 summarises the number of houses in Area 11 adopting these fabric and insulation energy efficiency measures.

Table 6: Existing energy efficiency measures in the housing stock in area of analysis.

Age band	Exterior walls	Roof	Ground floor	Glazing
Old -pre-1920	Solid, uninsulated	Insulated or uninsulated loft	Suspended (insulated or uninsulated)	Single (wood frame) or double (PVC)
Intermediate (1920-1979)	Cavity, filled or unfilled	Insulated or uninsulated loft	Suspended (insulated or uninsulated)	Single (wood frame) or double (PVC)
Recent (1980-present)	Cavity, filled	Insulated loft	Solid, edge-insulated	Double (PVC frame)
New (plan new build)	U-value=$0.2\,\mathrm{W\,m^{-1}\,K^{-1}}$	U-value=$0.13\,\mathrm{W\,m^{-1}\,K^{-1}}$	Solid, edge-insulated	Double (PVC frame)

Table 7: Breakdown of existing housing stock by exterior wall and window type in area of analysis.

Attribute	Number
Single-glazed houses	2878
Double-glazed houses	14863
Houses with solid (uninsulated) exterior walls	3602
Houses with cavity (unfilled) exterior walls	3078
Houses with cavity (filled) exterior walls	9585
Houses with no loft (mainly flats)	5461
Houses with uninsulated loft	1860
Lofts with up to 100mm insulation	1064
Lofts with 100 – 199mm insulation	4239
Lofts with > 200mm insulation	5501

Regarding heating systems, the predominant method of heating in the existing housing stock was found to be based on gas boilers with hot water radiators for space heating. A substantial majority of these will consist of gas ‘combi’ boilers with minimal domestic hot water storage. A breakdown of the existing heating systems by type can be found in Table 8.

3.3.3. Post-transition energy efficiency measures and heating electrification options

For the post-transition scenario, fabric insulation upgrades were taken to the maximum practically feasible as advised by NCC [26] and used by EPN [14] . Hence, the following

Table 8: Existing heating systems in area of analysis.

Heating system	Number
Gas boiler with radiators	15645
Oil boiler with radiators	9
Electric storage heating	705
Hybrid air-source heat pump	0
Air-source heat pump	0
Ground-source heat pump	0
District heating	1382

assumptions were taken. It was assumed that those houses with unfilled cavity walls would be upgraded with cavity fills and those houses with single-glazed windows would be upgraded to double-glazed windows. All uninsulated and partially-insulated loft spaces would be upgraded to at last 200mm of insulation. Solid external walls in older houses (3,602 houses) remain insulated as it was not considered practical or economic. This is inline with previous research findings [7]. Table 9 summarises the number of houses in Area 11 adopting these fabric and insulation energy efficiency measures.

Table 9: Post-transition energy efficiency measures in the housing stock in area of analysis.

Attribute	Number
Single-glazed houses	0
Double-glazed houses	17741
Houses with solid (uninsulated) exterior walls	3602
Houses with cavity (unfilled) exterior walls	0
Houses with cavity (filled) exterior walls	14139
Houses with no loft (mainly flats)	5461
Houses with uninsulated loft	0
Lofts with up to 100mm insulation	0
Lofts with 100 – 199mm insulation	0
Lofts with > 200mm insulation	12280

As to heating systems, the heating electrification options tested in this paper build upon these recommendations as well as the local authority own knowledge and policy requirements [26]. Three options were considered for the electrification of heat at transition (see Table 10).

Table 10: Heating systems electrification options.

Option	Description
MIXED	Partial electrification with a potential need for some local grid reinforcement.
IASHP	Independent air-and ground- source heat pumps giving full electrification with a potential need for extensive local grid reinforcement.
HPDH	Partial heat pump district heating with a balance of independent air -and ground- source heat pumps giving full electrification with a potential need for some local grid reinforcement.

MIXED heating electrification option

Based on the information provided by NCC [26] and EPN [14], for the MIXED case, a cautious approach to local grid reinforcement is considered through an incremental adoption of heat pumps as detailed in Table 11.

Table 11: Incremental adoption of heat pumps for depending on housing stock.

Houses with	Description of heat pump adoption
Old radiator systems	to have new low-grade radiators with air-source heat pumps and stored hot water.
Existing radiator system	not yet economic to replace (designed to operate at higher circulating temperatures) hybrid air-source heat pumps with gas-combi back up boiler units are used.
Large gardens	ground-source heat pumps are used.
Suitable boundaries	of the catchment area, near existing district heating plants, additions to district heating network connections are applied.

In summary, the numbers of heating systems forming the transitioned housing stock are given in Table 12.

Table 12: MIXED case: post-transition house heating systems in area of analysis.

Heating system	Number
Hybrid air-source heat pump	2768
Air-source heat pump	9069
Ground-source heat pump	384
Electric storage heating	203
District heating	5317

IASHP heating electrification option

For the IASHP case, all houses in Area-11 are assumed to be equipped with individual heat pumps including those houses currently connected to district heating networks . As in the previous case, the small number of houses enjoying ground-source heat pumps will be retained where practical (Table 13) but the vast majority will be air-source. Where necessary, heating systems are replaced with low grade emitters avoiding the need to use hybrid heat pumps.

Table 13: IAHSP case: post-transition house heating systems in area of analysis.

Heating system	Number
Hybrid air-source heat pump	o
Air-source heat pump	17357
Ground-source heat pump	384
Electric storage heating	0
District heating	0

HPDH heating electrification option

For the HPDH case, extensive centralised heat pump based district heating is used which reduces the need for local grid reinforcement. This option is considered feasible because of the existence of the river Tyne which flows through the city of Newcastle and would provide a potential source of heat for higher temperature district heating heat pumps. Since Area 11 projects inland from the river equivalent to roughly 2km of river stretch, a reasonable estimate is that 50% (see justification in Appendix A) of the houses in Area 11 might be potentially be heated by sourcing from the river (i.e. $2 \times 20 = 40$MW against a total peak load of 83.5 MW at transition).

In summary, the numbers of heating systems forming the transitioned housing stock are given in Table 14.

Table 14: HPDH case: post-transition house heating systems in area of analysis.

Heating system	Number
Hybrid air-source heat pump	0
Air-source heat pump	8486
Ground-source heat pump	384
Electric storage heating	0
District heating	8871

Performance metrics

The electrical demand of heat pumps (together with fuel demand in the case of hybrid heat pump systems) allocated to the post-transition housing stock were determined using results from recent UK field trails and low carbon heating evidence gathering studies [41, 42, 43]. Mean seasonal performance factors (SPFs) were deduced from these sources as representative of current commercial heat pump system behaviour in service[4] . For the river source, (district heating) option, a mean seasonal performance factor based on [45] was used. The performance metrics used are summarised in Table 15.

Table 15: Heat pumps performance metrics: mean seasonal performance factors (SPFs).

Heat Pump Type	SPF (seasonal mean)
Air-source heat pump	2.55 [41, 42]
Hybrid heat pumps	2.67[43], boiler efficiency=0.88; mean boiler load share=0.3.
Ground-source heat pump	2.76 [41]
River source district heating heat pumps	3 [45] [a]

[a]Given in this source as 'heating system CoPs' which include auxiliary loads (i.e. equivalent to the SPF) and based on 19 surface water source heat pumps monitored in Norway exhibiting seasonal heating system CoPs ranging from 2 to 4. This source also mentioned the Drammen heat pumps sourcing from the Oslo fjord with a seasonal CoP of 3 (the Drammen heat pumps have a collective capacity of 14MW and operate at elevated -but sesonally scheduled- heating water temperatures. For district heating, losses due to distribution equivalent to 10% of the annual energy use delivered by the network have been applied according to [46]

3.3.4. Other considerations

A survey of existing houses with photovoltaic arrays revealed a surprisingly small number of just 281 – less than 2% of the existing housing stock [14]. Further, the City Council

[4]Quantifying the likely extent of technological improvements on performance is outside the scope of this paper. It is clear is that performances advised by manufacturers tend to have an optimism bias when compared with performances in the field [44]. A more cautious approach by using available performance data from recent field monitoring studies of domestic heat pumps operating in UK conditions was adopted in this study

advise [26] that although there will be growth in the use of photovoltaics between now and 2050, it is unlikely to increase greatly among the existing housing stock due to the gradual reductions in feed-in-tariff payments. This, and the relatively modest contribution of solar in this high northern latitude application, meant that photovoltaic array contributions were, therefore, neglected from the analysis. Further, the existing and post-transition scenarios focus on heating electrification options and no assumptions are made with regards to other demand and supply side measures other than energy efficiency measures so as to follow EPN methodology.

3.4. Modelling framework

3.4.1. Community Energy Model: BREDEM-12

A Community Energy Model (CEM) has been developed based on the BREDEM-12 domestic building energy modelling method has been applied to the selected case study area. The CEM software modelling approach is a MATLAB®-coded tool based on BREDEM-12 [36] modelling method and has been applied for local building energy analysis and load profile synthesis.

BREDEM-12 is a two-zone monthly-average energy simulation method that relates well to national datasets and considers the key determinants which explain domestic energy consumption [36]. That is, dwelling's size and type are the significant building variables for energy consumption as demonstrated by [40] in their analysis of 924 English households and BREDEM-12 effectively captures those building variables for energy consumption prediction [38].

In terms of comfort assumptions, each BREDEM-12 modelled house archetype is split into two zones; the main living space and the balance of all other spaces. Comfort air temperatures are specified for the main living space and for the balance zone. It is also possible to specify the proportion of the balance zone volume that is heated (the balance being unheated). Because the comfort temperatures specified form the thermostat settings used for heating control, air temperatures (rather than comfort operative temperatures) are deployed. In all cases, the main living space temperature as set at 21 °C and the heated proportion of the balance zone was set at 18 °C. Two heating periods were defined for each week day – a 2-hour morning period and a 6-hour evening period. At weekends one 16-hour heating period was set for each weekend day.

Though using most of the BREDEM-12 energy calculation algorithms, CEM differs in two respects. First, whilst BREDEM-12 is essentially for single house modelling, CEM has been developed to read parametric modeling data (e.g. fabric attributes) for a large number of houses from a file. Second, alternative heating system performance metrics than those used in the standard BREDEM-12 method have been applied such as the outlined heating electrification options (see Section 3.3.3).

3.4.2. Heat pump demand

Detailed heat pump demand calculation modelling has been conducted in this study. The result is then used to study the impacts of heat pumps on the local low voltage (LV) distribution networks. An approach based on After Diversity Maximum Demand (ADMD) has been used [47]. This approach focuses on the diversity of large numbers of electrical consumers or 'customers'. ADMD is used in the design of distribution networks where demand is aggregated over a large number of customers and represents the mean of peak demands for a group of customers. ADMD is the maximum demand observed for a group of customers over typically one year time. Field trial results from a low carbon network project called the Customer-Led Network Revolution (CLNR) have been used [48].

The customer led network revolution project has explored the impact of 3 kWhheat pumps (HP) on ADMD based on field trial results of heat pumps [48]. The results have been adopted by distribution network operators for low voltage network design. ADMD for residential customers with and without HP can be found in [48]. Based on these findings, ADMD for residential customers with and without HP is depicted in Fig. 8 for customer groupings of up to 100. As can be observed, in both cases, ADMD reduces when the number of customers increases. This is due to the increased diversity in consumption when the number of customer increases.Following an analysis of extensive sets of data from a wide range of socio-economic groups it has been concluded that diversity variance becomes negligible at, typically, around 100 customers in a group [48]. This group size is used as a cut-off in the analysis that follows. The ADMDs for houses with and without heat pumps as reported in [48] are given here in eqns. 1 and 2 where N is the number of customers in a group

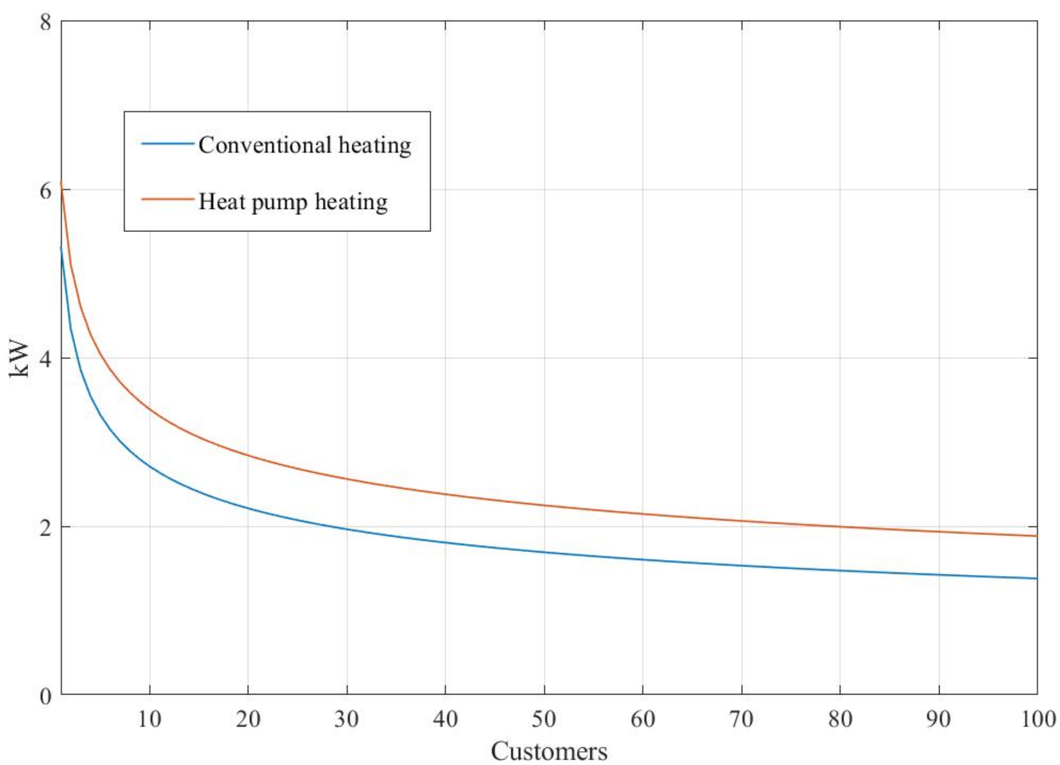


Figure 8: ADMD for residential customers with and without heat pump

Two curves in Fig. 8 are detailed below:

$$ADMD_{noHP} = 5.319\,\mathrm{N}^{-0.293} \tag{1}$$

$$ADMD_{HP} = 6.093\,\mathrm{N}^{-0.255} \tag{2}$$

3.4.3. Carbon emissions

For the carbon emissions, the greenhouse gas (GHG) emission factors for the UK were used [49] . A current set of values for 2017 were used to estimate GHG emissions due to the existing stock as a baseline. The values are 0.185 $\mathrm{kgCO_2e/kWh}$ for natural gas and 0.352 kg/kWh for UK grid electricity [49]. For the 2050 projection, a value for electric grid GHG emission is needed. A value of 0.059 $\mathrm{kgCO_2e/kWh}$ was used following the linearly extrapolated carbon intensity of delivered electricity (2008 to 2020) employed by Government Office for the South East [50]. Other predictions support the achievement of this figure by 2035 [51].

4. Validation

4.1. Postcode level data

Energy consumptions due to fuel[5] and electricity[6] from the present work are compared with postcode level metered consumptions for 2015 obtained from a survey carried out by the UK Department of Business, Energy and Industrial Strategy [52] [53]. The results are plotted as predicted total annual energy consumptions for viable postcodes in Area 11 against total metered energy for that postcode. Viable postcodes were taken to be those with data for both fuel and electricity and where the number of meters tallied with the number of houses in each postcode. There are a total of 714 postcodes in Area 11 and, of these, 222 were found to have viable data [52] [53]. The results are given in Fig. 9.

Both gas and electricity results from the CEM modelling tool compare favourably to the postcode level metered data for 2015 with a slight bias to over-prediction. The viable postcode totals for 2015 were 61.7 MW h (gas) [52] and 14.1 MW h (electricity) [53] where as the predicted totals were 65.2 MW h (gas) and 15.3 MW h (electricity).

4.2. National Energy Efficiency Data Framework

A further verification was done by comparing results of the present study with house energy consumption data provided by the UK's National Energy Efficiency Data Framework (NEED) [54].

The NEED data consists of energy consumptions by both house type and by floor area band. To compare results on a floor area band basis with equal weighting, it is appropriate to consider a uniform range of floor areas for each house type within each of the NEED floor area bands. For comparison, the model in the present work was applied to all basic house types and a range of floor areas rising in increments of 10 m^2 across all of the NEED floor area bands. Results for each house type were then averaged for all floor areas within each NEED band.

The overarching purpose of NEED is to monitor progress on energy efficiency improvement measures to the UK housing stock. It might, therefore, be anticipated that the NEED data will be biased towards houses with insulation upgrades. For this reason, results were

[5]Fuel or thermal demand are equivalent terms in this paper

[6]Electricity consumption in this paper refers only to lighting and appliances

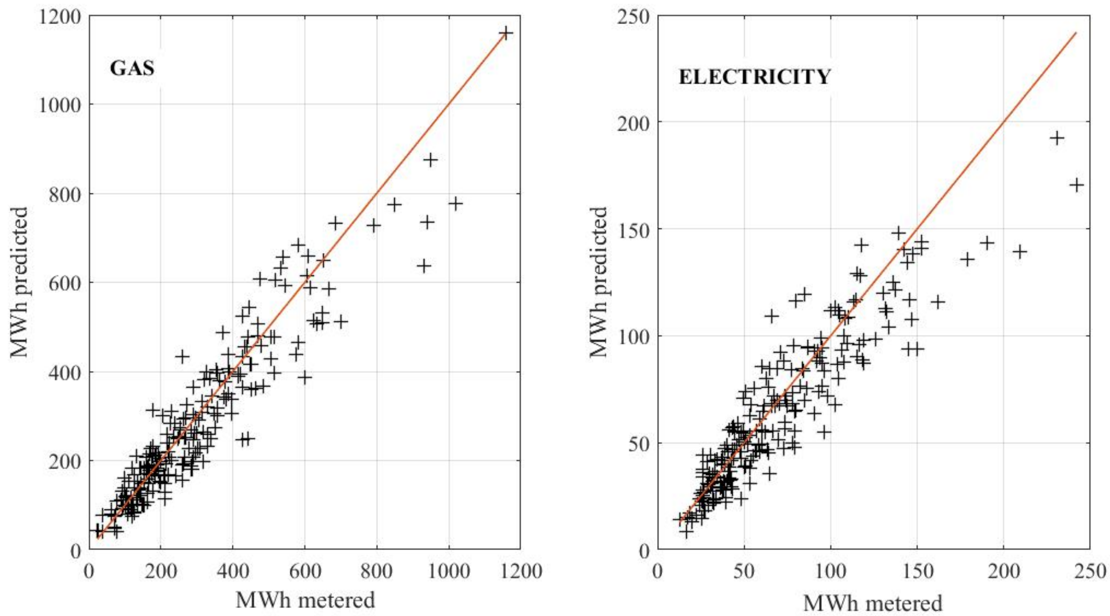


Figure 9: Predicted postcode totals plotted against metered totals

generated in the present work for Area 11 houses in both their existing conditions and, for comparison, all houses with fabric insulation upgrades to the maximum practical extent that might be feasible after transition pathways (post-transition scenario). Results are given in figures 10 (annual fuel [7], MWh, by house total floor area (TFA)), 11 (annual electricity [8], MWh, by house TFA) and 12 (annual fuel, MWh, by house type).

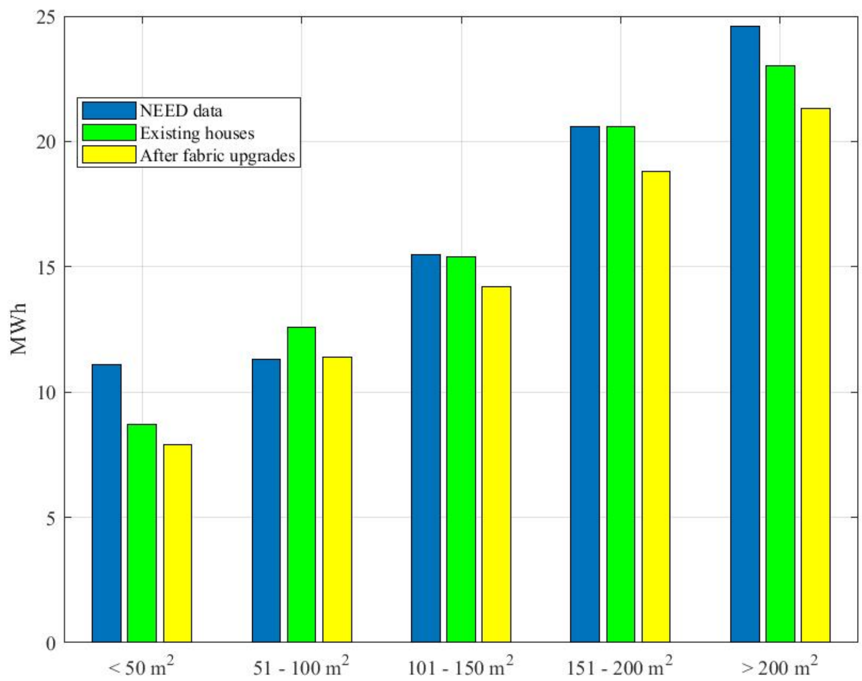


Figure 10: NEED comparison with present work -annual fuel by floor area band

In general the results compare favourably with a tendency for the present work fuel predictions to be higher than NEED at house type level but lower at floor area basis. Because NEED reflects housing across the whole UK these results will make a uniform account of all regional biases due to different methods of construction, regional weather and owner/occupier economic circumstances. The latter in particular may well be behind the tendency for NEED to show consistently higher electrical consumption than the present work shows (Fig. 11). As expected, the fuel results with insulation improvements consistently show lower fuel use than NEED but not greatly so.

[7]the term annual fuel is fuel used for heating and domestic hot water – it does not include any electricity or electric heating (these results reflect gas-heated houses only)

[8]the term annual electricity is due to lighting and electrical appliances. It does not include any fixed electric heating

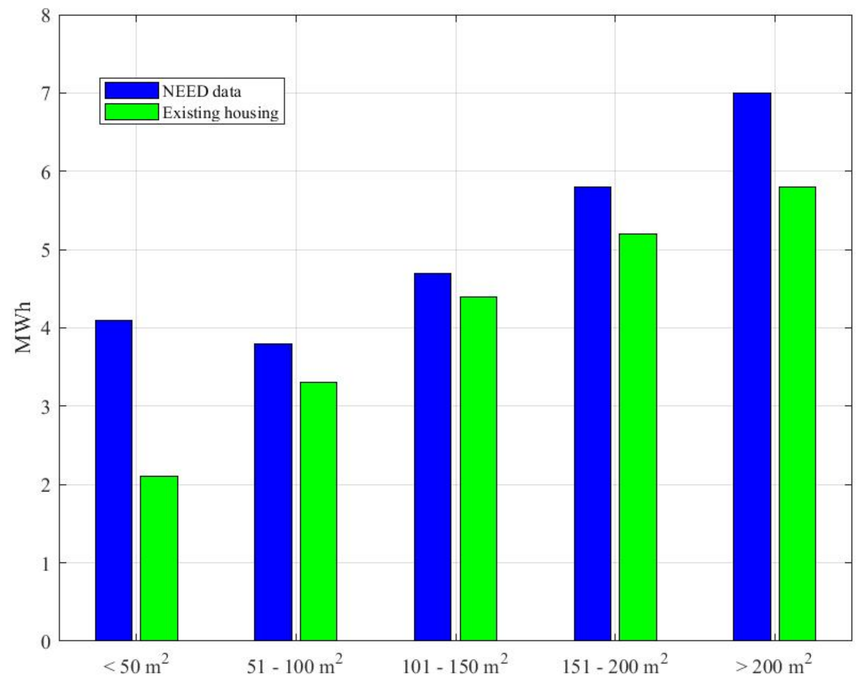


Figure 11: NEED comparison with present work -annual electricity by floor area band

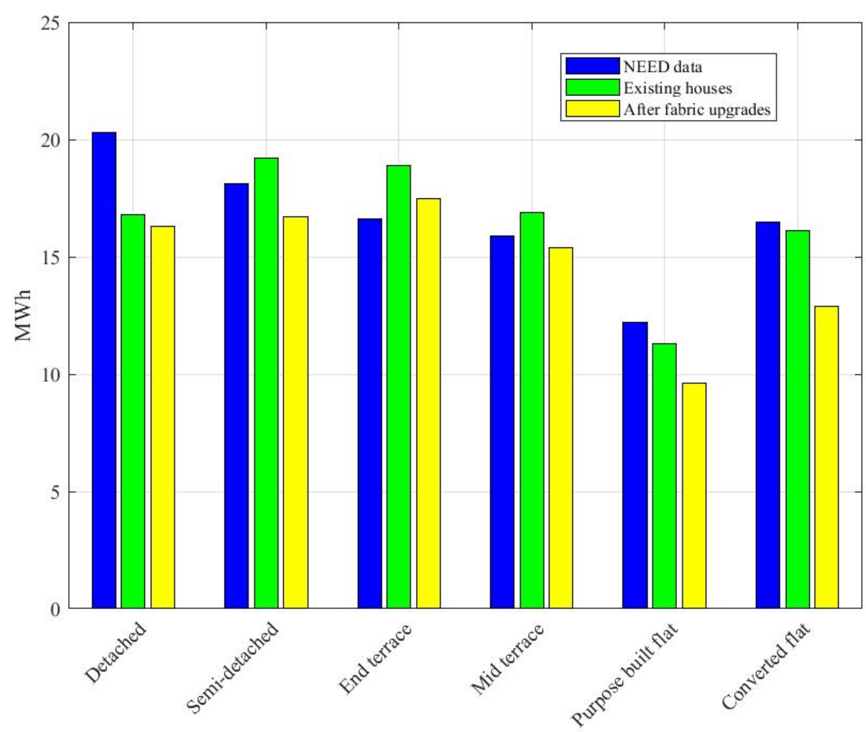


Figure 12: NEED comparison with present work-annual fuel by house type

5. Results

5.1. Building energy modelling

To enable a direct comparison, energy modelling results are presented for both the existing housing stock of Area-11 and the same housing after the transitioning upgrades described in Section 3.4. Results are presented in figures 13- 16. In these figures, 'Mixed' refers to an incremental transition to electrification involving some hybrid (gas/electric) heat pumps, 'IASHP' refers to independent air-source heat pumps (with a small number of ground-source heat pumps where practical) and 'HPDH' refers to the partial river source district heating heat pump option with a balance of individual air-source heat pumps.

Figure 13 and 14 show mean annual house electricity demand by both house type and floor area (TFA – the most significant single parameter affecting energy use). As might be expected, the post-transition electricity demand shows significant increases due to the transfer of large numbers of houses to heat pumps. The relatively small increase in electricity use by purpose-built flats after transition is because many of the existing purpose-built flats (mostly in tower blocks) used of electric storage heating. Though the 'Mixed' option shows the lowest overall increase due to the continued use of some gas in houses using hybrid heat pumps, it still represents significant increase (see Figure 13).

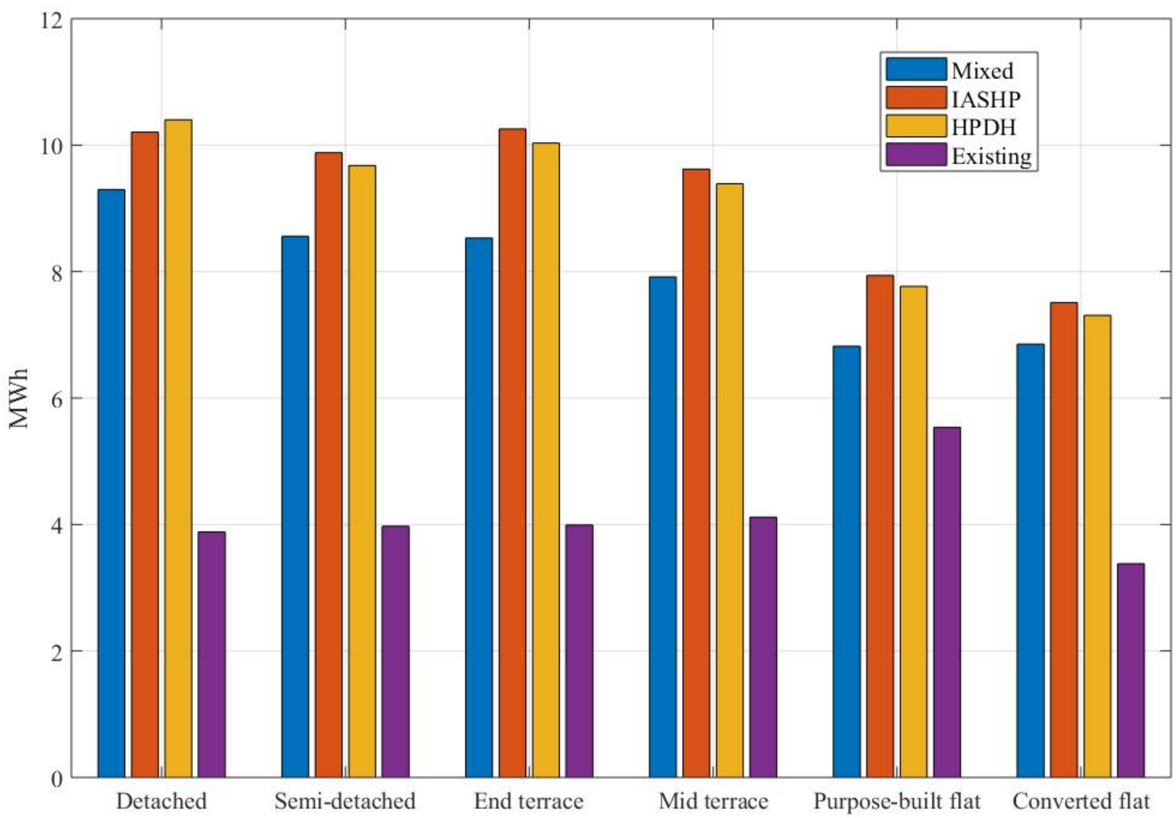


Figure 13: Mean annual electricity demand by house type. See numerical values in Table B.18 in Appendix B

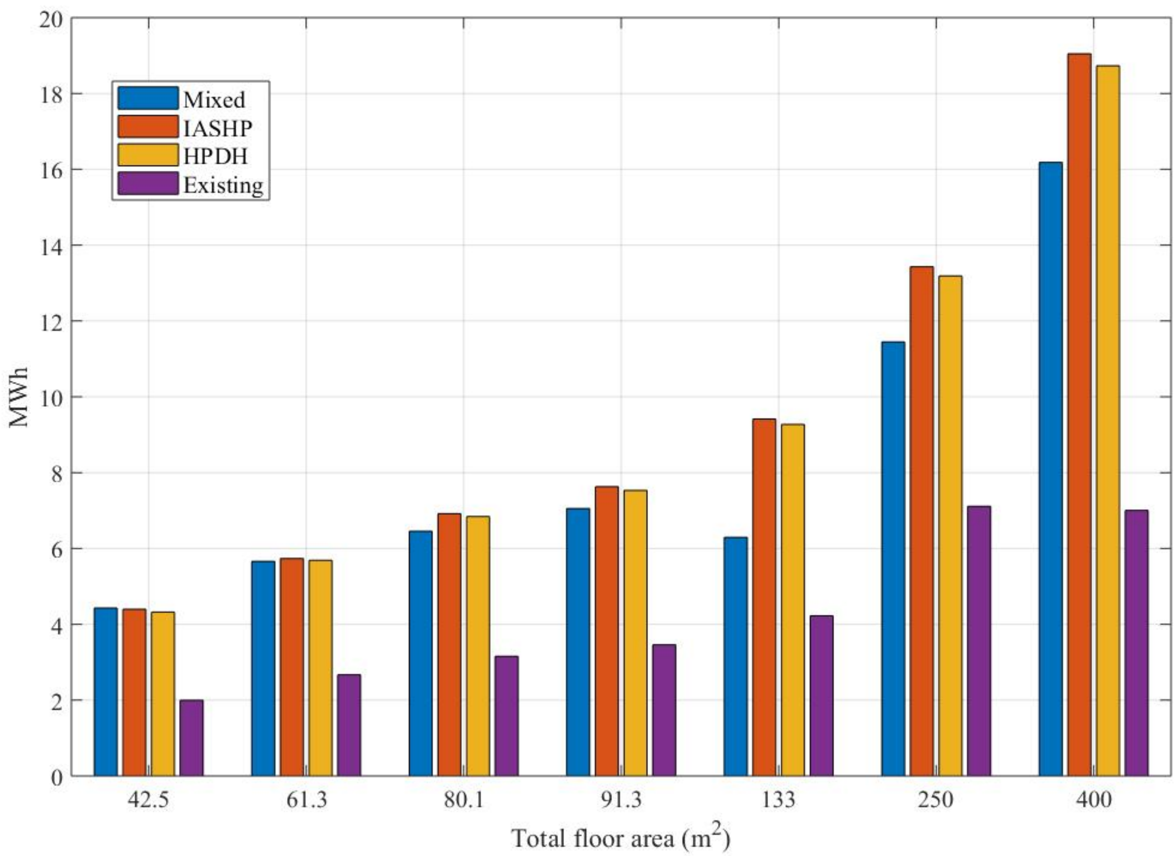


Figure 14: Mean annual electricity demand by house TFA. See numerical values in Table B.19 in Appendix B

Figure 15 and 16 show the mean house peak electricity use (electrical capacity) in kW again by house type (Fig. 15) and house TFA (Fig. 16). Again the significant increase in electrical capacity is evident especially for the larger houses. The relatively large increase indicated for the 'Mixed' strategy for larger detached houses is because a relatively large number of these house types were allocated to this option. These results will be used in the next section to consider the impact of increases in electrical capacity on the local electrical grid network.

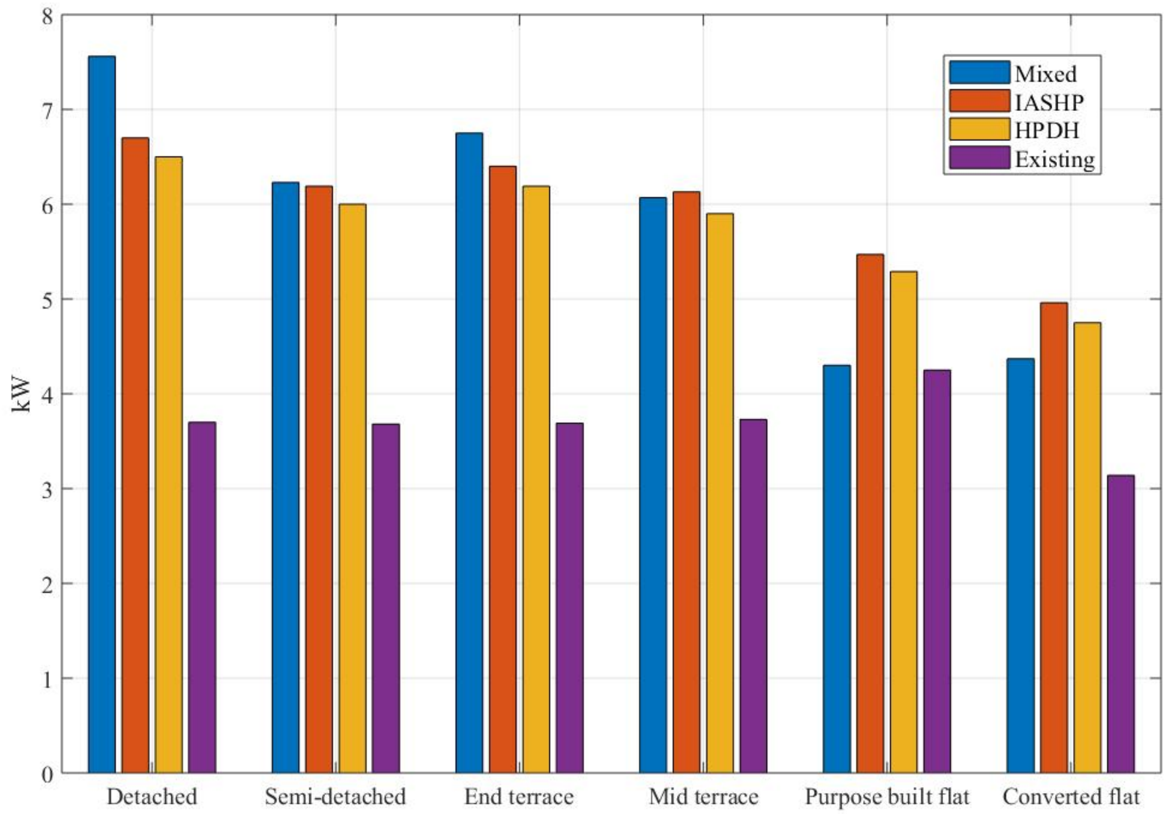


Figure 15: Mean peak electricity demand by house type. See numerical values in Table B.20 in Appendix B

In summary, Table 16 gives the total annual energy consumptions due to fuel and electricity, together with the sum of peak electrical capacities (i.e. before diversity allowances) and current and projected annual carbon emissions arising for Area 11. The carbon emissions given in this table are in Tonne-CO_2e/year.

5.2. Heat pump demand calculation

An indication of the extent of the required increase in electrical capacity due to the use if heat pumps is shown in Fig 17. which gives a box-whisker representation of the postcode level mean household electrical consumption (MWh) for all three options compared with the

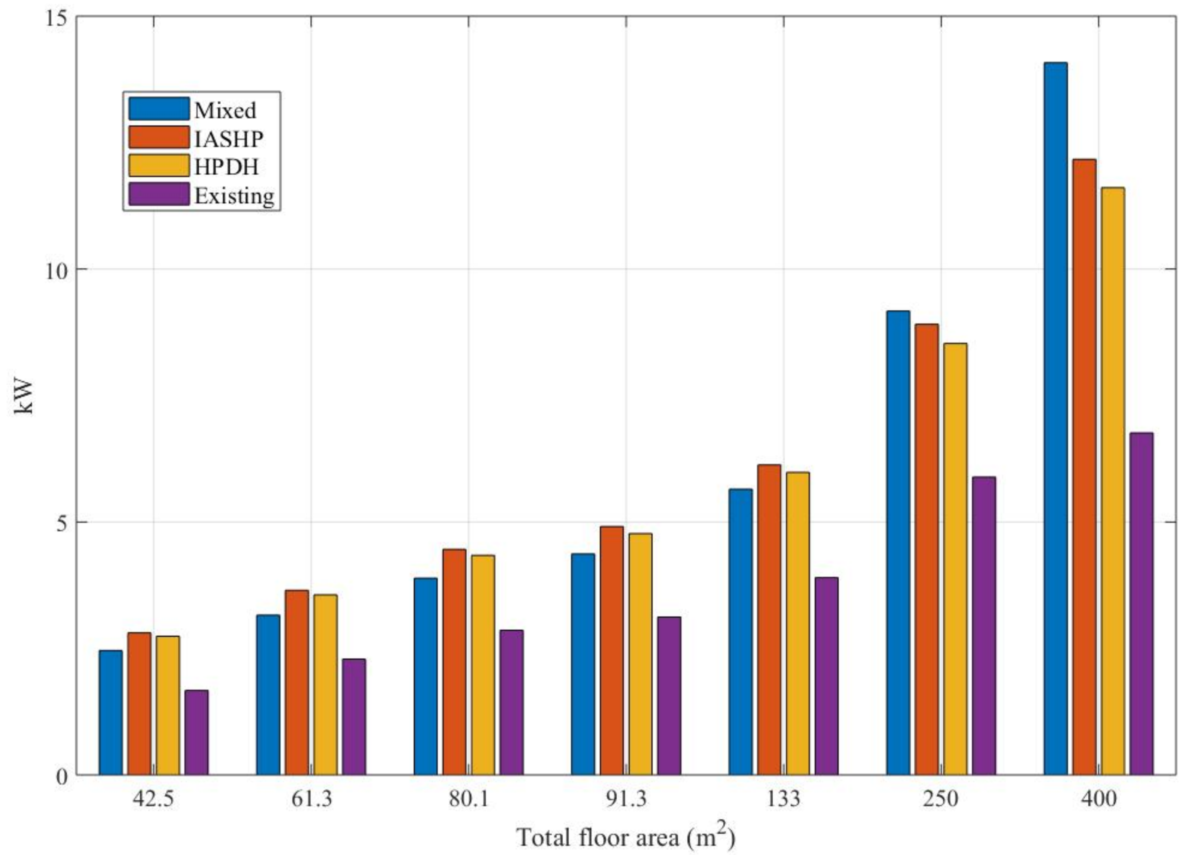


Figure 16: Mean peak electricity demand by house TFA. See numerical values in Table B.21 in Appendix B

Table 16: Annual energy use for Area 11

Energy use	CASE			
	Existing	Mixed	IASHP	HPDH
Annual electricity (GWh)	67.4	114.1	143.1	140.6
Annual fuel (GWh)	250.4	91.8		
Sum of peak electricity (MW)	59.0	76.6	91.9	89.4
Sum of peak HP electricity (MW)		18.5	32.6	30.2
Sum of peak DH electrictiy (MW)				14.3
Current annual carbon emission (T)	70,048	57,150	50,365	49,503
Projected (2050) carbon emission (T)	55,894	33,187	20,318	19,970

existing meter data. As explained in Section 4.1, only the viable postcodes have been used in this comparison (222 viable postcodes out of a total of 714 in Area 11). All electrification options entail significant increases in demand over the existing meter-based consumptions. Note that for the district heating option ('HPDH') the electricity demand at postcode level excludes the power required to drive the district heating heat pumps because this will not arise at street level and will, therefore, not of itself entail grid reinforcement (though new electrical infrastructure will of course be needed at the energy centre(s)). However approximately 50% of the houses in this option still use independent heat pumps and so some increase in demand is necessary. As might be expected, a wider spread of electrical consumptions is evident for those two options in which all space heating is derived from electric heat pumps (i.e. 'HPDH' and 'IASHP').

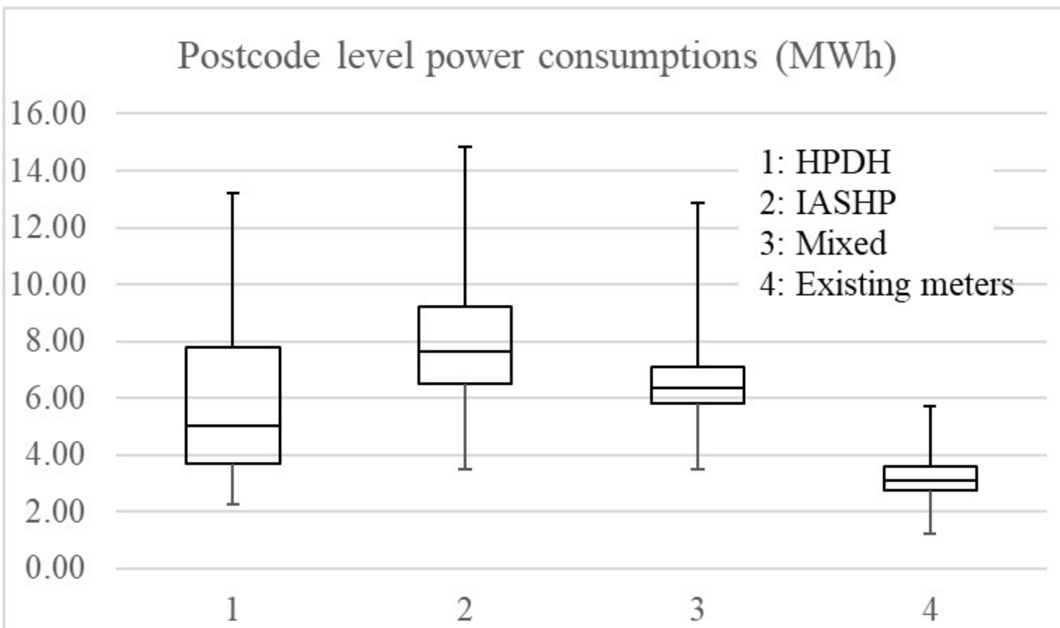


Figure 17: Postcode level mean annual house electricity demands

As per the method presented in Section 3.4.2 , the average number of existing houses served by the electrical 55 LV sub-stations in Area 11 is 285. Eqns. 1 and 2 therefore suggest an average sub-station level effective diversity factor for Area 11 of $285^{-0.293} = 0.19$. The modelled sum-of-peak power for all existing houses in area 11 is 59MW as given 16 so at each sub-station on average the peak ADMD will be $(59MW/55) * 0.19 = 0.203MW(203kW)$. For the mixed case the diversity factor is $285^{-0.255} = 0.237$ and so the average peak sub-station ADMD will be $(76.6MW/55)*0.237 = 0.33MW(330kW)$. This represents an increase in ADMD sub-station demand for the mixed case over and above the existing of $(0.33 - 0.203)/0.203 = 63\%$. As far as annual consumption is concerned, the median postcode level power consumption for the existing stock is 3.11 MWh. For the mixed case, it is predicted to be 6.37 MWh -17. This represents an increase in median postcode cluster demand of $100 * (6.37 - 3.11)/3.11 = 105\%$

Similarly, for the IASHP strategy (a full roll-out of independent heat pumps: mainly air-source with a small number of ground-source) the average increase in peak electrical demand will be 95% (0.396MW) and the median increase in electricity consumption will be 145% (7.63MWh). Finally, for the HPDH strategy, where it has been estimated that 50% of the housing analysed in this work could have heating needs met by centralised river water-source heat pumps. With the approach detailed previously, an increase in peak sub-station electrical demand of 59% (0.323 MW) will arise and the increase in median electricity consumption will be 61% (5.02 MW). Note that the HPDH strategy benefits from having a large component of its load (14.3 MW) met centrally at the heat pump energy centre which will not contribute to local grid demands at sub-station level.

6. Discussion

In this section, the implications of the presented work are discussed in terms of: the impact of heat electrification on the local electricity network for selected areas within the city; energy planning models and local policy; carbon emission savings; and area-based heat electrification project delivery.

6.1. Peak and annual mean electricity demand

Local policy makers were interested in establishing the range of additional electrical demands patterns as the installation of heat pumps will lead to a significant increase of overall annual median household electricity demand but also, more importantly, to peaks in electricity demand as they operate at specific peak times and for sustained periods such as morning and early periods in winter. Thus, it is peak requirement rather than average or total consumption which determines the scale and resulting impact of the necessary supporting infrastructure [30].

Table 17: Peak LV sub-station electrical and annual median increase postcode cluster demand

	CASE		
	Mixed	IASHP	HPDH
Peak LV sub-station electrical demand (%)	63	95	59
Annual median increase postcode cluster demand (%)	105	145	61

To that extend, the results of this research show that the electrification of heat at city-scale will have a substantial impact on the local electrical grid infrastructure and provide a first indication of what the potential additional mean and (winter) peak household electricity demand ranges are shown in Table 17 at sub-city level. Furthermore, as expected, the IASHP strategy has the most substantial impact on the local electricity network as it has the greatest increase on peak sub-station and annual median electricity demand. Whilst these increases are high ranging from 59-95% on peak LV sub-station demand, they are significantly lower than what local policy makers might have ascertained from existing literature at national level. For instance, Fawcett et al. [29] calculated the total electricity demand and peak if "all heating were supplied via heat pumps" at a country scale and, for the UK, the "ratio between peak and mean electricity demand is 4.1". Similarly, [30] notes that at UK national level, based on energy output, peak gas demand for heat at 300GW is: "5 times greater than the level would be if it were spread evenly over the days and seasons; 12 times the summer maximum; between 5 and 6 times the current peak in the electricity system" [30, p. 20]. Figure 18 illustrates this.

In terms of energy planing models and local policy, it is known that bottom-up and spatially referenced domestic building level frameworks, like the one presented in this paper, provide a more robust way of modelling local area characteristics such as building related or socio-economic data and therefore able to estimate domestic energy end-use demand at sub-city area more confidently [38]. This paper goes further. This paper highlights the significance of modelling at sub-city scales as this enables a more accurate quantification of peak and annual median increase demands at appropriate scales for local intervention: sub-station electrical and postcode cluster. Moreover, the modelling consideration of: local knowledge (e.g. HPDH case), heat pump performance metrics and heat pump demand (i.e. ADMD) has a significant impact on determining potential additional mean and (winter) peak household electricity demand ranges.

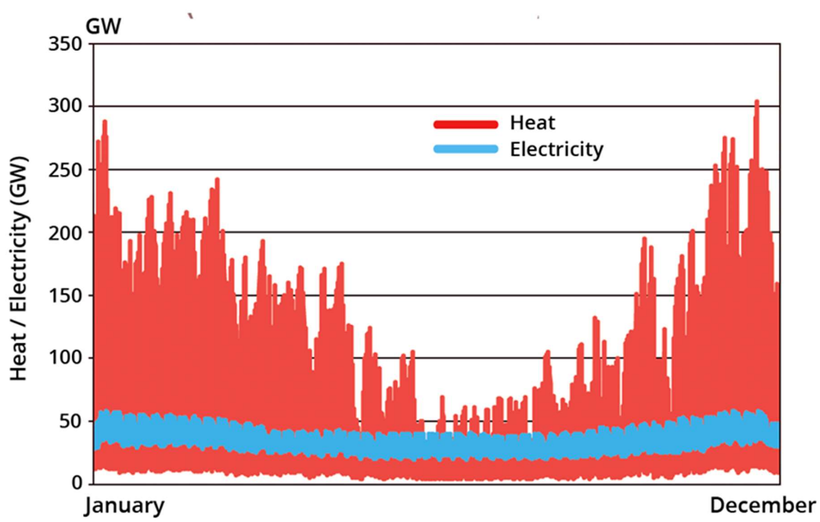


Figure 18: UK actual half hour electricity demand in 2010 with a synthesised half hourly heat demand. [55]

6.2. Carbon emissions

The results of this paper show that emission savings will be achieved with all options studied. A 53% reduction in carbon emission will arise with the mixed electrification strategy, rising to 71% and 72% with a full roll-out of heat pump based heating in independent and district heating-supported strategies respectively. However, even if nothing is done, it is estimated that carbon emissions will reduce by 20% in 2050 due to the reduction in GHG intensity of future electricity generation. The results of this paper also show that it is not possible to achieve complete decarbonisation (i.e. as set out in the 100% Clean Energy vision [16]) of heat via a full heat electrification in the selected area of study even with the most ambitious strategy (i.e. HPDH case). This is significant and it should seen with the context of the paper's scope and findings.

In other words, it is likely that the decarbonisation of domestic heat in the selected case will rely on a combination of district heating networks and heat pumps. However, district heating is not currently deployed at scale to areas of low rise residential areas in Newcastle and, unless current and planned heat networks in the urban city centre are developed to act a seed for wider growth, it is unlikely that current planned heat networks outside the city centre will be developed.

Consequently, local policy makers are well advised to fully explore heating electrification options within the city as technological development will aid the city to achieve its long-term ambition. In practice, this will mean a rethinking of the entire "urban energy landscape, from buildings, to transport, to industry and power" [56, p. 1] at the right scale. This means flexible coupling of energy supply and demand, via for instance smart technologies [57] and rigorous planning, and integration of power and heat sector [58] are necessary to achieve 100% renewable integration and decarbonisation. Further, this convergence of electricity, heat, transport will be potentially more disruptive when coupled with urban data as noted by [59] when outlining the European energy system convergence of digitalisation, decarbonisation and decentralisation. This is explored in the next section by proposing specific steps for a more integrated and across end-use (e.g. buildings, transport and industry) and transformation (e.g. power and heat) sectors modelling approach to local energy planning electrification using the case study as a way of example.

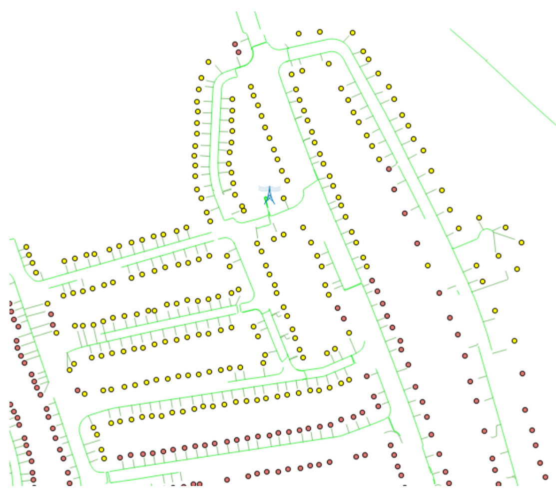
6.3. Heat electrification project delivery

The case study area was spatially defined based on high voltage (HV) electrical substation locations so as to ascertain the impact on heating electrification options on the local grid. This paper shows that whilst that spatial scale is appropriate for strategic heating electrification planning, it is insufficient for area-based project delivery. The results of this paper show a single heating option across the spatial area of analysis will not be sufficient to achieve the city's targets. However, this strategic spatial thinking also reveals, there are neighbourhoods within Area 11 which might be suitable for an area-based heat electrification project delivery. For example, when looking at the LV electrical substation spatial scale, it was possible to identify specific neighbourhoods where local heating electrification was the only possibility for decarbonation as they were too removed from any planned District Heating Network planned. Figure 19 show the housing stock whose electricity is fed by a specific LV substation. In Figure 19b, the light colour dots represent individual houses associated to the LV substation represented in the figure by an electric tower.

Whilst this is helpful to the local authority, in the case study area, the introduction of greener urban mobility solutions such as Electric Vehicles could have a larger impact in both ascertaining local peak electricity demand at sub-station level and carbon emissions reduction. Specifically, as buildings and transport become more interlinked with the power system, there will be a need to balance the demand and supply of electricity and provide flexibility as renewable technologies, storage options and smart grid and controls take-up increases. In particular, there will be a need to investigate the potential for Demand Side Response(DSR) measures. The potential for using demand flexibility to reduce the cost of operating electricity networks have been widely explored in the literature by [60, 61, 62] but, more recently, their associated risks have also been highlighted by [63].

This will mean that city level policy makers will need to a spatially referenced (e.g. UPRN), more detailed and integrated modelling approach at this scale (i.e. LV electricity substation) to cope with the challenges that increasing electric mobility, distributed generation and storage, as well as smart grids and controls when moving from the planning to the design phase in heating electrification. At a building level, this approach will need a representative sample of house types (see Fig. 19b) over short time intervals in order to capture transient electrical demands and their interaction with the more damped (but seasonal) heating demand patterns. Furthermore, it will be necessary to build LV network models with detailed cable and transformer modelling in a steady state analysis so as to study load flows. This type of]approach will enable the investigation of following outstanding questions: a) Incorporate thermal storage and model-reference adaptive control of the heating systems; b) investigate the impact of local battery storage; c) Investigate the impact of electric vehicle growth on local charging demands; d) develop strategies for smart control utilising both thermal and battery storage as well as electric vehicle charging; and e) Investigate the impact of possible reductions in electrical demand due to improved user awareness and information (smart metering) and evolving changes in human behaviour and response to energy use and climate change.

(a) Areal view.



(b) Schematic view. Light (yellow) colour dots represent individual houses associated to the LV substation. LV is represented in by an electric tower icon.

Figure 19: Areal and schematic view of domestic housing stock fed by one LV substation. As per real data provided by the Newcastle City Council.

7. Conclusions

The study presented in this paper builds upon EPN's whole-system local energy planning outputs and modelling assumptions and presents an area-based modelling approach to heat electrification using 17,741 dwellings in the city of Newcastle upon Tyne as a case study. The presented framework has been developed so as to address local energy policy questions on the impact of electrification of residential heat. These questions reflect current issues and under-researched research challenges such as the quantification of peak electricity demand for heat pumps based electrification options.

The results of this paper quantify annual median and peak household electricity demand for an area-based roll out of heat pump based electrification options in a case study area with 17,741 domestic dwellings. These results show that the electrification of heat at city-scale will have a substantial impact on the local electrical grid infrastructure and provide a first indication of what the potential additional mean and (winter) peak household electricity demand ranges are shown in Table 17 at sub-city level. The results reveal that the increases of peak electricity demand are high ranging from 59-95% on peak LV sub-station demand but they are lower than what might be ascertained from existing literature at national level. This paper further highlights the significance of modelling at sub-city scales as this enables a more accurate quantification of peak and annual median increase demands at appropriate scales for local intervention: sub-station electrical and postcode cluster. Moreover, the modelling consideration of: local knowledge (e.g. HPDH case), heat pump performance metrics and heat pump demand (i.e. ADMD) has a significant impact on determining potential additional mean and (winter) peak household electricity demand ranges.

The results also show that emission savings will be achieved with all options studied but achieving the city's ambitious decarbonisation goals (i.e. 100% Clean Energy vision [16]) will remain out of reach even with the most ambitious of the currently considered area-based local electrification strategies (i.e. HPDH case). Hence, it is likely that a combination of district heating networks and heat pumps, and technological development will be needed to achieve the city's long-term goals. Finally, the paper further underpins the significance of sub-city modelling by enabling policy makers to move from strategic heating electrification planning at a high voltage spatial scale to identifying housing neighbourhoods at LV sub-station for area-based delivery. However, to move from planning to the design phase, an integrated modelling approach to cope with forthcoming system design challenges at LV scale is suggested

Acknowledgements

We would like to thank the Energy Path Networks team for their support, Grant Tuff in particular. We would like to thank the Energy Technology Institute and the Smart Systems Catapult for supporting this work and Peter Dempsey in particular for coordinating the work. We are very grateful to Newcastle City Council for providing support from their Energy and GIS teams. In particular, we would like to thank Adrian Mcloughlin and Brian Williams for their policy and technical support respectively.

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Appendix A. A

In terms of the river's suitability, river flow and temperature are crucial. The mean river flow measured at Bywell, a few kilometres upstream from Newcastle city centre, has been observed to be $45.097\,\mathrm{m^3\,s^{-1}}$ [64]. Whereas for winter temperature, 30-year mean temperatures in winter months (October to March) show variations of between 4 °C and 8 °C (though predominantly not more than 6 °C) [65]. To protect marine species, any temperature change imposed in the course of utilising naturally occurring water in the UK must be restricted to 2 K If the indicated mean river flow is reduced by this amount, then a peak source energy of 378MW would be available. That is, with a mean heat pump seasonal performance ration of 3, this would provide a peak heating rate of 567MW. In this present work, the estimated peak space heating demand after transition for Area 11 is 83.5 MW. Assuming all 139,000 houses in Newcastle have the same average heating demands as Area 11, then the projected demand for the whole of Newcastle's housing stock would be 654MW and so the river would be unable to heat all houses in Newcastle (not to mention houses on the Gateshead bank of the river). Furthermore, previously reported assumptions about the maximum practical heat extraction from the UK's rivers suggest a maximum of 20MW (heating system capacity) per 1km of river stretch.

Appendix B. Appendix B

Results presented in a table format.

Table B.18: Raw date behind Figure 13

House type	CASE (MWh)			
	Mixed	IASHP	HPDH	Existing
Detached	9.297	10.205	10.401	3.883
Semi-detached	8.559	9.88	9.677	3.974
Mid terrace	8.53	10.256	10.033	3.992
End terrace	7.915	9.62	9.389	4.115
Purpose-built flat	6.818	7.94	7.765	5.537
Converted flat	6.852	7.51	7.308	3.379

Table B.19: Raw date behind Figure 14

m^2	CASE (MWh)			
	Mixed	IASHP	HPDH	Existing
42.5	4.429	4.397	4.322	1.999
61.3	5.662	5.734	5.688	2.672
80.1	6.456	6.917	6.845	3.155
91.3	7.054	7.637	7.53	3.463
133	6.294	9.416	9.271	4.225
250	11.447	13.429	13.187	7.114
400	16.181	19.045	18.729	7.004

Table B.20: Raw date behind Figure 15

House type	CASE (MWh)			
	Mixed	IASHP	HPDH	Existing
Detached	7.56	6.7	6.5	3.7
Semi-detached	6.23	6.19	6.0	3.68
Mid terrace	6.75	6.4	6.19	3.69
End terrace	6.07	6.13	5.9	3.73
Purpose-built flat	4.3	5.47	5.29	4.25
Converted flat	4.37	4.96	4.75	3.14

Table B.21: Raw date behind Figure 16

m^2	CASE (MWh)			
	Mixed	IASHP	HPDH	Existing
42.5	2.46	2.81	2.74	1.67
61.3	3.16	3.65	3.56	2.29
80.1	3.89	4.46	4.34	2.86
91.3	4.37	4.91	4.77	3.12
133	5.65	6.13	5.98	3.9
250	9.17	8.91	8.53	5.89
400	14.08	12.17	11.61	6.76